

Transition from Baryon- to Meson-Dominated Freeze Out – Early Decoupling around 30 A GeV?

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Abstract. The recently discovered sharp peak in the excitation function of the K^+/π^+ ratio around 30 A GeV in relativistic heavy-ion collisions is discussed in the framework of the Statistical Model. In this model, the freeze-out of an ideal hadron gas changes from a situation where baryons dominate to one with mainly mesons. This transition occurs at a temperature $T = 140$ MeV and baryon chemical potential $\mu_B = 410$ MeV corresponding to an energy of $\sqrt{s_{NN}} = 8.2$ GeV. The calculated maximum in the K^+/π^+ ratio is, however, much less pronounced than the one observed by the NA49 Collaboration. The smooth increase of the K^-/π^- ratio with incident energy and the shape of the excitation functions of the Λ/π^+ , Ξ^-/π^+ and Ω^-/π^+ ratios all exhibiting maxima at different incident energies, is consistent with the presently available experimental data. The measured K^+/π^+ ratio exceeds the calculated one just at the incident energy when the freeze-out condition is changing.

We speculate that at this point freeze-out might occur in a modified way. We discuss a scenario of an early freeze-out which indeed increases K^+/π^+ ratio while most other particle ratios remain essentially unchanged. Such an early freeze-out is supported by results from HBT studies.

1. Introduction

The NA49 Collaboration has recently performed a series of measurements of Pb-Pb collisions at 20, 30, 40, 80 and 158 A GeV beam energies [1, 2, 3]. Combining these results with measurements at lower beam energies from the AGS [4, 5, 6, 7, 8, 9] they reveal a sharp variation with beam energy in the $\Lambda/\langle\pi\rangle$, with $\langle\pi\rangle \equiv 3/2(\pi^+ + \pi^-)$, and in the K^+/π^+ ratios. Such a strong variation with energy does not occur in pp collisions and therefore indicates a major difference in heavy-ion interactions. A strong variation with energy of the $\Lambda/\langle\pi\rangle$ ratio has been predicted on the basis of arguments put forward in [10]. It has also been suggested recently in Ref. [11] that this might be a signal of the critical point in the QCD phase diagram at high baryon density.

In this paper we explore another, less spectacular, possibility for the sharp maximum. The arguments for this will be presented in two steps. In step (i) the Statistical Model of a hadron gas is studied. For this purpose, we investigate various quantities along the freeze-out curve [12, 13] as a function of $\sqrt{s_{NN}}$. It is shown that the entropy of the hadronic gas is dominated at the lower energies by baryons and at the higher ones by mesons. The transition occurs just at the energy where the sharp maximum has been observed. In step (ii) we speculate whether at these incident energies the freeze-out might happen earlier. The consequences are discussed and arguments based on HBT results are presented to support this idea.

2. Maximum relative strangeness content in heavy-ion collisions around 30 A GeV

The experimental data from heavy-ion collisions show that the K^+/π^+ ratio rises from SIS up to AGS. It is larger for AGS than at the highest CERN-SPS energies [2, 12, 14, 15, 16] and decreases even further at RHIC [17]. This behavior is of particular interest as it could signal the appearance of new dynamics for strangeness production in high-energy collisions. It was even conjectured that this property could indicate an energy threshold for quark-gluon-plasma formation in relativistic heavy-ion collisions [1].

In the following we analyze the energy dependence of strange to non-strange particle ratios in the framework of a hadronic Statistical Model. In the whole energy range, the hadronic yields observed in heavy-ion collisions resemble a system in chemical equilibrium characterized by two parameters, the temperature T and the baryon chemical potential μ_B . These two parameters define the “freeze-out curve” which seems determined by the condition of fixed average energy/particle $\simeq 1$ GeV [12, 13]. As the beam energy increases in the energy domain of SIS and AGS, T rises and μ_B decreases slightly. Above AGS energies, T exhibits only a moderate change and converges to its maximal value in the range of 160 to 180 MeV, while μ_B is strongly decreasing.

Rather than studying the K^+/π^+ ratio, we use the ratios of strange to non-strange particle multiplicities (Wroblewski factor) [18] defined as $\lambda_s \equiv \frac{2\langle s\bar{s} \rangle}{\langle u\bar{u} \rangle + \langle d\bar{d} \rangle}$ where the quantities in angular brackets refer to the number of newly formed quark-antiquark

pairs, i.e. it excludes all quarks that were present in the target and the projectile nuclei.

Applying the Statistical Model to particle production in heavy-ion collisions calls for the use of the canonical ensemble to treat the number of strange particles, particularly for data in the energy range from SIS up to AGS [19]. The calculations for Au-Au and Pb-Pb collisions are performed using a canonical correlation volume [19]. The quark content used in the Wroblewski factor is determined at the moment of *chemical freeze-out*, i.e. from the hadrons and, especially, hadronic resonances before they decay. This ratio is thus not an easily measurable observable unless one can reconstruct all resonances from the final-state particles. The results are shown in Fig. 1 left as a function of $\sqrt{s_{NN}}$.

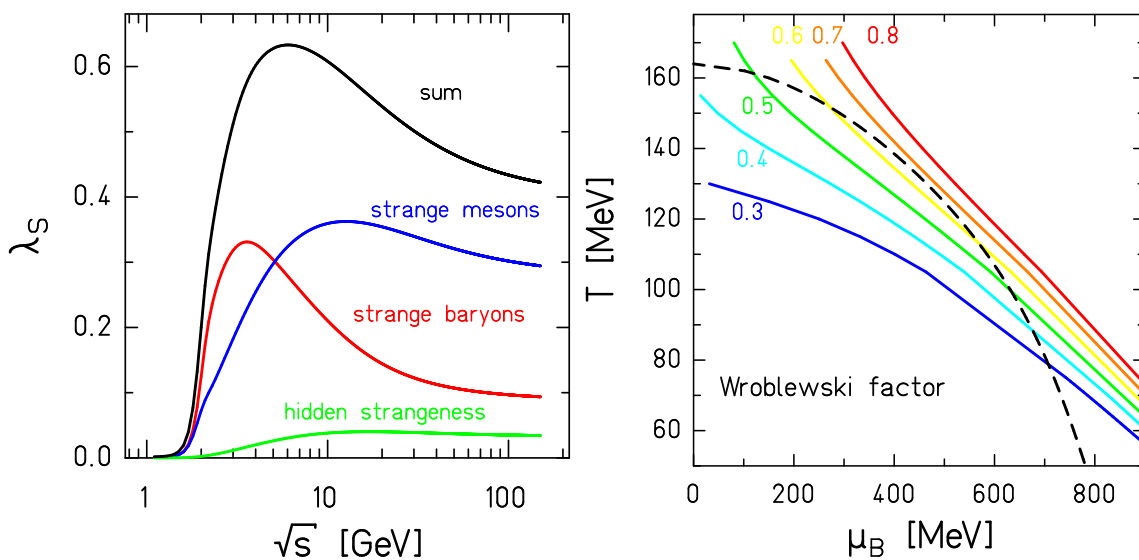


Figure 1. Left: Contributions to the Wroblewski factor λ_s (for definition see text) from strange baryons, strange mesons, and mesons with hidden strangeness. The sum of all contributions is given by the full black line. Right: Lines of constant Wroblewski factor λ_s in the $T - \mu_B$ plane (solid lines) together with the freeze-out curve (dashed line) [12].

The solid line (marked “sum”) in Fig. 1 describes the Statistical-Model calculations in complete equilibrium along the unified freeze-out curve [12] with the energy-dependent parameters T and μ_B . From Fig. 1 we conclude that around $\sqrt{s_{NN}} = 8.2$ GeV corresponding to an incident energy of 30 A GeV, the relative strangeness content in heavy-ion collisions reaches a clear and well pronounced maximum. The Wroblewski factor decreases towards higher energies and reaches a limiting value of about 0.43. For details see Ref. [20].

The appearance of the maximum can be traced to the specific dependence of μ_B and T on the beam energy as also pointed out in Ref. [21]. Figure 1 (right) shows lines of constant λ_s in the $T - \mu_B$ plane. As expected, λ_s rises with increasing T for fixed μ_B . Following the chemical freeze-out curve, shown as a dashed line in Fig. 1, one can see that λ_s rises quickly from SIS to AGS energies, then reaches a maximum

at $\mu_B \approx 500$ MeV and $T \approx 130$ MeV. These freeze-out parameters correspond to 30 A GeV laboratory energy. At higher incident energies the increase in T becomes negligible but μ_B keeps on decreasing and as a consequence λ_s also decreases.

The importance of finite baryon density on the behavior of λ_s is demonstrated in Fig. 1 left, showing separately the contributions to $\langle s\bar{s} \rangle$ coming from strange baryons, from strange mesons and from hidden strangeness, i.e. from hadrons like ϕ and η . As can be seen in Fig. 1, the origin of the maximum in the Wroblewski ratio can be traced to the contribution of strange baryons. The production of strange baryons dominates at low $\sqrt{s_{NN}}$ and loses importance at high incident energies when the yield of strange mesons increases. However, strange mesons also exhibit a broad maximum. This is due to associated production of e.g. kaons together with hyperons at the lower incident energies.

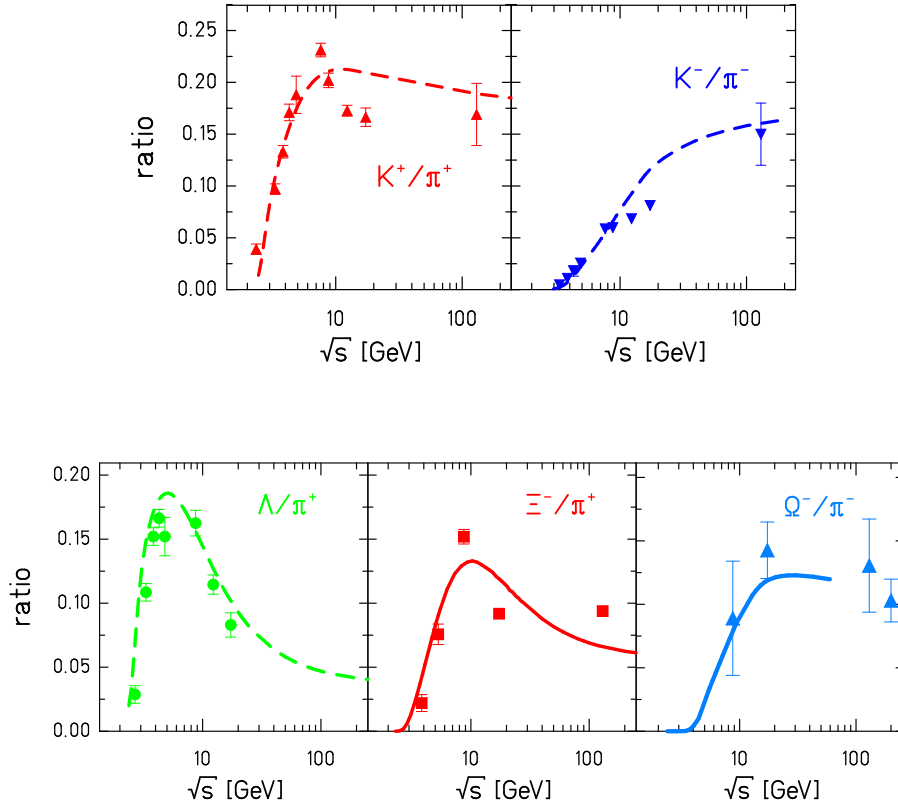


Figure 2. Ratio of strange-to-non-strange mesons (upper part) and the corresponding ratios for baryons (lower part) as a function of $\sqrt{s_{NN}}$.

Figure 2 shows the comparison of the Statistical Model [20] and 4π data (except for RHIC data, above $\sqrt{s_{NN}} = 130$ GeV). As can be understood from the arguments above, the ratio Λ/π exhibits the most pronounced maximum, K^+/π^+ a weaker one and K^-/π^- has no maximum at all.

It is worth noting that the maxima in the ratios for multi-strange baryons occur at ever higher beam energies. This can be seen clearly in Fig. 2 for the Ξ^-/π^+ ratio which

peaks at a higher value of the beam energy. The ratio Ω^-/π^+ also shows a (very weak) maximum, as can be seen in Fig. 2. The higher the strangeness content of the baryon, the higher in energy is the maximum. This behavior is due to a combination of the facts that the baryon chemical potential decreases rapidly with energy and the multi-strange baryons have successively higher thresholds.

It is to be expected that if these maxima do not all occur at the same temperature, i.e. at the same beam energy, then the case for a phase transition is not very strong. The observed behavior seems to be governed by properties of the hadron gas. More detailed experimental studies of multi-strange hadrons will allow the verification or disproval of the trends shown in this paper. It should be clear that the Ω^-/π^+ ratio is very broad and shallow and it will be difficult to find a maximum experimentally.

In general, the model gives a good description of the data. It shows a broad maximum in the K^+/π^+ ratio while the data exhibit a sharp peak. The drop towards 158 A GeV is most pronounced when using 4π yields as done in these figures. This decrease is less pronounced for midrapidity values [2].

3. Transition from baryonic to mesonic freeze-out

While the Statistical Model cannot explain the sharpness of the peak in the K^+/π^+ ratio, there are nevertheless several phenomena giving rise to the rapid change which warrant a closer look at the model.

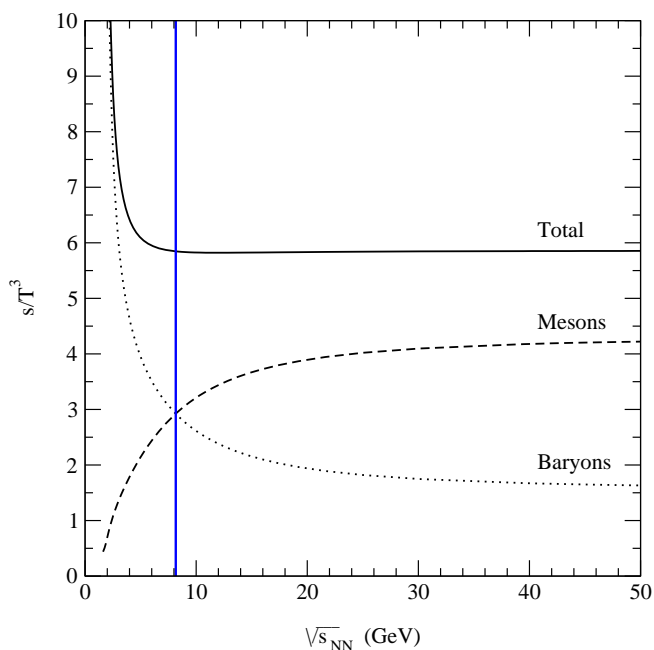


Figure 3. The entropy density normalized to T^3 as a function of the beam energy as calculated in the Statistical Model using THERMUS [22].

To get a better estimate of the thermal parameters in the transition region we show in Fig. 3 the entropy density as a function of beam energy following the freeze-out curve given in [12]. The separate contribution of mesons and of baryons to the total entropy is also shown in this figure. There is a clear change of baryon to meson dominance around $\sqrt{s_{NN}} = 8.2$ GeV. Above this value the entropy is carried mainly by mesonic degrees of freedom. It is remarkable that the entropy density divided by T^3 is constant for all incident energies except for the low-energy region corresponding to the SIS energy region.

4. Origin for a possible deviation from the freeze-out curve

In this section, we explore the possibility that freeze-out might happen earlier in the transition region. For this interpretation, we show in Fig. 4 the calculated values of the K^+/π^+ ratio for various combinations of T and μ_B as contour lines with the corresponding values given in the figure. The thick solid line reflects the locations of the freeze-out given by the condition of Ref. [12]. If freeze-out happens around an incident energies of 30 A GeV at higher T , then the ratio K^+/π^+ will be higher. This ratio can never exceed a value of 0.25 in an equilibrium condition.

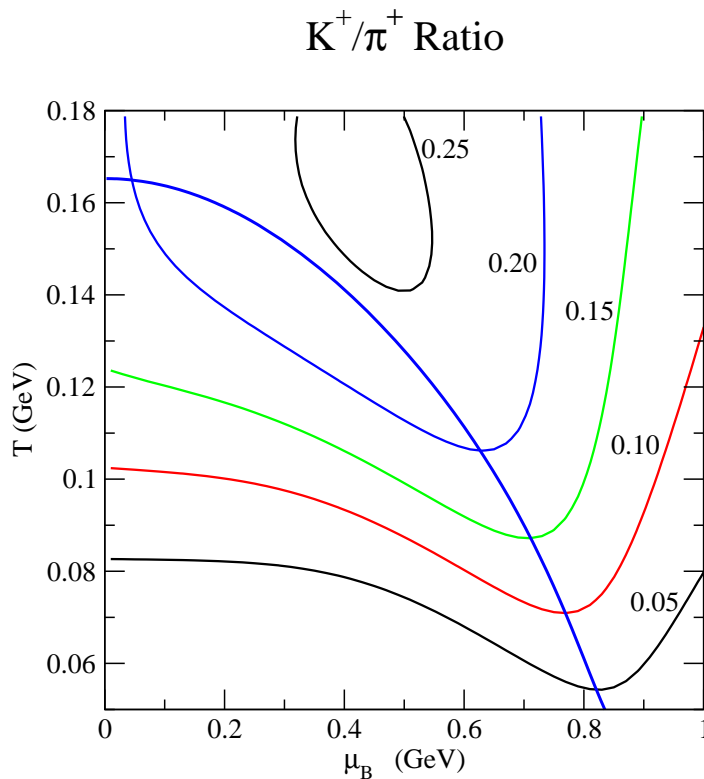


Figure 4. Values of the K^+/π^+ ratio for combinations of T and μ_B are given by the contour lines and the corresponding values. The thick line refers to the freeze-out curve [12].

It turns out that other particle ratios are less affected by a different freeze-out scenario, as their variation in the $T - \mu_B$ plane is very different [23].

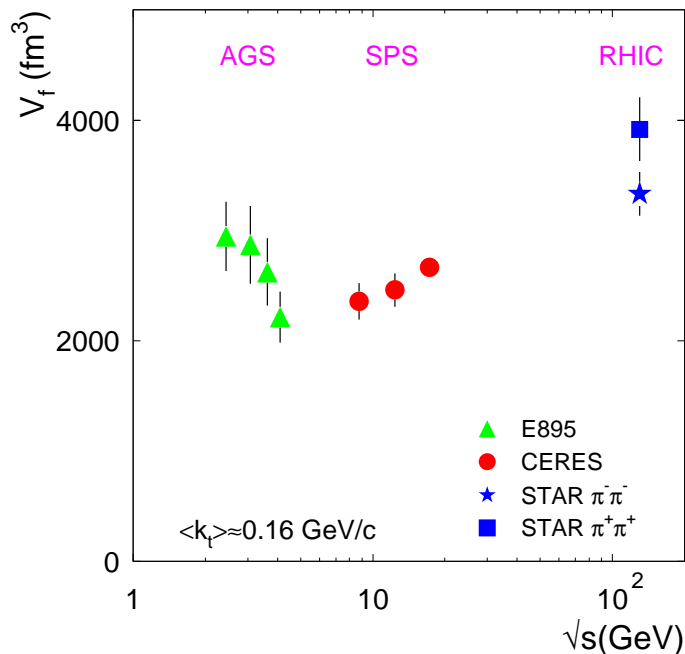


Figure 5. Freeze-out volumina as extracted from HBT studies [24].

An early freeze-out is supported by results from HBT studies [24]. Figure 5 shows the extracted volumina as a function of $\sqrt{s_{NN}}$. Between top AGS and the lowest SPS energies a minimum can be seen. As the fireball is expanding, a smaller volume reflects an earlier time. The authors of Ref. [24] relate this minimum to a change in the interaction from πN to $\pi\pi$.

5. Summary

It has been shown that the Statistical Model yields a maximum in the relative strangeness content around 30 A GeV. This is due to a saturation in the temperature T while the chemical potential keeps decreasing with incident energy. Since the chemical potential plays a key role, it is clear that baryons are strongly affected. Indeed, all hyperon/ π ratios yield maxima. In contrast, the K^-/π^- ratio shows a continuously rising curve as expected from the arguments above. The K^+/π^+ ratio, however, exhibits a maximum, as K^+ mesons are sensitive to the baryo-chemical potential due to their associate production with hyperons. The model predicts that for different hyperon/ π ratios the maxima occur at different energies. If experiments prove this, the case for a phase transition is strongly weakened.

The energy regime around 30 A GeV seems to have specific properties. It is shown that the entropy production occurs below this energy mainly via creation of baryons, while at the higher incident energies meson production dominates.

In a third section, we speculated on the impact of a change in the freeze-out condition which might lead to an early freeze-out, thus deviating from the usual freeze-out condition. Such a scenario would increase the K^+/π^+ while leaving other particle ratios essentially unchanged. HBT studies show that around 30 A GeV a minimum in the extracted volumina occurs. This could be interpreted as an earlier kinetic freeze-out and might indicate also another freeze-out for chemical decoupling.

This work was supported by the German Ministerium für Bildung und Forschung (BMBF) and by the Polish Committee of Scientific Research.

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